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# Soil Aggregate- and Particle-Associated Organic Carbon under Different Land Uses in Nepal

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Soil aggregation is an important process of C sequestration and hence a useful strategy to mitigate the increase in concentration of atmospheric $CO_2$. We studied water stability of soil aggregates (WSA) and soil organic carbon (SOC) associated with aggregates and primary particles in surface (0–10 cm) and subsurface (10–20 cm) layers of cultivated (*khet*, irrigated lowland, and *bari*, rainfed upland) and forest lands (dense *Shorea* forest, degraded forest and shrub land, pine–*Shorea* forest, *Shorea*–pine–*Schima* forest, and *Schima*–*Castanopsis* forest) in a mountain watershed of Nepal. Macroaggregates (>2 mm) were abundant in forest soils (41–70%) while microaggregates (<0.5 mm) were abundant (56–63%) in cultivated lands. Pine mixed forest contained more macroaggregates in both layers. Mean WSA in the surface soil was highest in *Shorea*–pine–*Schima* forest (96%) and lowest in *khet* (74%). Macroaggregates in the surface layers contained 14.9 to 24.8 and 5.5 to 20.7 g $kg^{-1}$ SOC in cultivated and forest soils, respectively, while microaggregates contained 12.5 to 30.8 and 11.9 to 25.4 g $kg^{-1}$ SOC, respectively. The forest soils contained more sand (639–834 g $kg^{-1}$) and fewer clay particles (49–95 g $kg^{-1}$) than the cultivated soils. Soils under natural forest, however, were characterized by higher SOC associated with all primary particles. Cultivated soils contained higher amounts of clay but less clay-associated SOC than forest soils. The relation between clay content and clay-associated SOC was explained by a quadratic function ($R^2$ = 0.45, $P$ = 0.002).

Abbreviations: BD, bulk density; CEC, cation exchange capacity; DF, degraded forest and shrub land; DS, dense *Shorea* forest; PS, pine–*Shorea* forest; SC, *Schima*–*Castanopsis* forest; SNK, Student–Newman–Kuels test; SOC, soil organic carbon; SOM, soil organic matter; SPS, *Shorea*–pine–*Schima* forest; WSA, water stability of soil aggregates.

Soil can be source or sink of atmospheric C depending on land use, cropping system, and management practices (West and Marland, 2002; Lal, 2003a; Singh and Lal, 2005). Soil C sequestration through enhanced aggregation is an important strategy of judicious soil management to mitigate the increasing concentration of atmospheric $CO_2$ (Shrestha et al., 2004; Bronick and Lal, 2005). Soil organic C associated with aggregates is an important reservoir of C, protected from mineralization because it is less subjected to physical, microbial, and enzymatic degradation (Trujilo et al., 1997; Bajracharya et al., 1998). Soil aggregate size distribution and stability are important indicators of soil physical quality, reflecting the impact of land use and soil management (Castro Filho et al., 2002) on aggregation or degradation (Boix-Fayos et al., 2001; Barthes and Roose, 2002) and soil health (Herrick et al., 2001). Land use, management, and local climate also influence soil aggregation and aggregate stability (Bergkamp and Jongejans, 1988; Cerda, 2000). Soil organic matter (SOM) and soil texture are the principal determinants of physical properties such as bulk density and aggregate stability (Young, 1988). The latter depends largely on the associated SOC and clay contents (Boix-Fayos et al., 2001). Conversion of soil from forest to other land uses results in higher bulk density, lower hydraulic conductivity, and higher susceptibility to erosion (Spaans et al., 1989; Lal, 2003b), thereby exacerbating soil degradation and decline in SOC concentration (Lal and Kimble, 1997). Farming practices affect SOC concentration and physical properties (Gami et al., 2001; Hao et al., 2001). Tillage operations disrupt soil structure and accentuate SOM oxidation by increasing aeration, which stimulates microbial activity (Vance, 2000). In contrast, conservation tillage or no-till have less deleterious effects on soil structure, and maintain or increase SOC concentration (Lal and Kimble, 1997).

The interaction of clay colloids with organic compounds and inorganic cementing materials creates soil aggregates by forming organo-mineral complexes. It is the arrangement of these secondary particles and the pore spaces among them that determines the soil structure. Thus, soil structure and SOM concentration are among

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the most dynamic properties of soil, and depend on land use and management (Blanco-Canqui and Lal, 2004). Therefore, knowledge of aggregate stability is useful in the evaluation of soil properties with regard to land use systems. The water stability of soil aggregates (WSA) determined in the laboratory is a measure of the soil's susceptibility to erosion, compaction, and other disruptive forces. Surface flow of water and raindrop impacts are primary sources of energy causing soil aggregate disintegration in the field, and thus the attendant soil erosion. Aggregate-associated C provides strength and stability, however, and counters the impact of destructive forces. Losses of C from macroaggregates are usually more rapid than those from microaggregates due to a lower protective effect of biophysical and chemical processes (Jastro and Miller, 1998).

Soil texture is another key determinant of soil quality. Textural composition moderates the behavior of several soil processes, including SOM dynamics and C sequestration (Kettler et al., 2001). Physical fractionation of soil particles into size and density classes can provide information on the importance of interactions between organic and inorganic soil components and the turnover of SOM (Christensen, 2001). The degree of association of SOC with particle sizes is a qualitative indicator of the impact of land use and soil management. The SOC associated with the coarse fraction is commonly less decomposed material and has a higher C/N ratio than that associated with the fine fraction. In contrast, SOC sorbed to clay is mostly of humic nature with a low C/N ratio (Christensen, 2001). The SOC associated with the sand fraction is a labile pool of C and reflects rapid changes in SOM quality due to changes in land use and management. The SOC in the clay fraction, however, is more stable and is altered more by physical and chemical process than by land use changes (Khanna et al., 2001).

A high population growth in Nepal is rapidly changing land use and land cover (Ives, 1987; Shrestha et al., 1999). Attendant soil erosion and nutrient losses are serious problems on sloping lands (Tripathi et al., 1999; Gardner and Gerrard, 2003; Sitaula et al., 2004), middle mountain regions, which comprise 30% of Nepal's land area (Government of Nepal, 1989). These regions are characterized by a high population density and low per capita cultivated land area of 0.15 ha (Central Bureau of Statistics, 2003). Several studies (Tripathi et al., 1999; Thapa and Paudel, 2002; Gardner and Gerrard, 2003) have indicated that upland sloping terraced (*bari*) soils are more prone to degradation processes than soils under other land uses. Gardner and Gerrard (2001) reported soil erosion of 3 to 10 Mg ha$^{-1}$ under *Shorea robusta* C.F. Gaertn. forest at various stages of degradation. Awasthi (2004) reported an annual soil erosion rate of 32.3 Mg ha$^{-1}$ from grazing land and 18.9 Mg ha$^{-1}$ from *bari* in a Middle Hill watershed of Nepal. These rates were presumably related to land use and management, and the underlying mechanism and processes were not identified.

A review of available literature indicates that different land use and management practices have a strong effect on soil properties, especially aggregation and SOC dynamics. Such effects vary spatially and temporally. Yet, there is a paucity of information on the mechanisms and magnitudes of SOC associated with aggregate- and particle-size fractions under different tree species and land uses under specific Nepalese conditions. The dynamics of SOC and N in relation to particle size have rarely been studied.

Therefore, the objective of this study was to investigate aggregate- and primary particle-associated SOC concentrations in soils under dominant land uses in the Middle Hills of Nepal, where land use change is progressing rapidly and the risks of soil degradation are high.


**Fig. 1. Location map of the study area with reference to Nepal and South Asia.**

## MATERIALS AND METHODS

### Study Area

This study was conducted in the Pokhare Khola watershed in Nepal (Fig. 1). It is a middle mountain watershed located between 27°46′28″ to 27°48′06″ N and 84°53′32″ to 84° 55′11″ E, covering an area of about 530 ha. The watershed consists of moderate to very steep slopes, with altitude ranging from 400 to 1100 m above sea level (Government of Nepal, 1994). Predominant soils in the watershed comprise Cambisols (Inceptisols) followed by Luvisols (Alfisols) in the lower elevation and Leptosols (Lithic subgroups of these orders) in some of the degraded forest areas, according to the FAO classification system (Sherchan et al., 2003). Climatic data from 1987 to 2001 showed monthly average maximum and minimum temperatures of 31.3 and 8.3°C in the months of May and January, respectively (Fig. 2). The mean annual rainfall is 1650 mm, with the highest rainfall of 441 mm in July and minimum of 9.8 mm in November. The main drainage in Pokhare Khola flows from south to north, discharging into the Trishuli River.

The watershed area can be divided into forest (59%) and cultivated (41%) land uses. On the basis of forest condition and tree species composition, forests can be further categorized into five systems, as presented in Table 1. There are two distinct types of cultivated lands, namely, rainfed upland (*bari*) and irrigated lowland (*khet*). The *khet* land is usually terraced and bunded, growing paddy rice (*Oriza sativa* L.) in a puddle soil and is sometimes followed by wheat (*Triticum aestivum* L.) or other winter crops. Off-season vegetable cultivation is also becoming popular, and thus wheat production has declined in the study area. *Bari* land is terraced or sloping and not bunded, where farmers grow crops of maize (*Zea mays* L.)

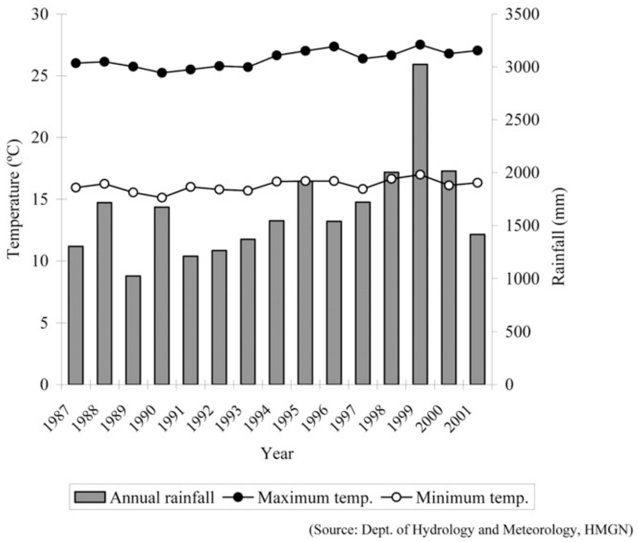


**Fig. 2. Annual rainfall and average maximum and minimum temperature in Pokhare Khola watershed from 1987 to 2001.**

alone or mixed with legumes such as soybean [*Glycine max* (L.) Merr. or cow peas (*Vigna unguiculata* L.) during the rainy season, followed by finger millet (*Eleusine coracana* L.). In both cultivated lands, land preparation is done by wooden plow driven with oxen or manually by hand hoe. Thus, the plow layer is not more than 20 cm. *Bari*, being in proximity of the farmsteads, gets more farmyard manure than *khet* land, while *khet* receives more chemical fertilizer than *bari*. Chemical fertilizer use is increasing in this area with increase in cropping intensity (Sherchan et al., 2003). Broadleaf tropical forest occurs at lower altitudes (<500 m), while the middle altitudinal zone (500–800 m) has mixed pine (*Pinus roxbourgii*) forest and the upper elevation zone has temperate broadleaf forest. Forests were in a degraded condition until the 1980s due to deforestation. After implementation of community forest programs, it is getting better in terms of vegetation cover. Vegetation cover is becoming better in the managed DS forest as a result of better management by local people where *Shorea robusta* stands dominate. Degraded forest and shrub lands are forest areas that have has a long-term history of livestock grazing. The pine mixed forests are of two catergories: one mixed with *Shorea robusta*, while the other additionally has *Schima wallichii* (DC.) Korth. The upper altitudinal zone is dominated by temperate broadleaf trees of *Schima walichii* and *Castanopsis indica* (Roxb. ex Lindl.) A. DC. Since the forests occur in steep areas, they are well protected and represent relatively pristine forest.

**Table 1. Description of land uses in the Pokhare Khola watershed.**

| Land use† | Area covered | Cropping pattern or major vegetation |
|---|---|---|
| | ha | |
| *Bari* | 164.6 | Maize–millet–vegetable, maize–millet–fallow, maize–vegetable–vegetable, maize–mustard–fallow |
| *Khet* | 54.4 | Rice–wheat–rice, rice–vegetable–maize, rice–vegetable–vegetable |
| DS | 173.6 | *Shorea robusta, Lagestromia parviflora, Acacia catechu, Dalbergia sisoo* |
| DF | 42.2 | *Shorea robusta, Lagestromia parviflora, Acacia catechu, Dalbergia sisoo, Pinus roxburghii, Schima walichii* |
| PS | 8.6 | *Pinus roxburghii, Lagestromia parviflora, Shorea robusta* |
| SPS | 11.0 | *Schima walichii, Pinus roxburghii, Shorea robusta* |
| SC | 76.4 | *Schima walichii, Castanposis indica, Syzygium cumunii* |

† *Bari*, rainfed upland; *khet*, irrigated lowland; DF, degraded forest and shrub land; DS, dense *Shorea* forest; PS, pine–*Shorea* forest; SC, *Schima–Castanopsis* forest; SPS, *Schima*–pine–*Shorea* forest.

## Soil Sampling

Soil samples were collected from the surface (0–10 cm) and subsurface (10–20 cm) soil layers of four sites randomly chosen at different locations of each land use system. Sample collection was done during September in *bari* and forest land uses, while soil samples for *khet* land use were collected in October 2004. Soil profiles of 40 by 40 cm were excavated, and soil samples for bulk density (BD) measurements for each depth were obtained with core samplers (5 cm in diameter and 6 cm high). Bulk soil samples to measure and compute average soil parameters were collected randomly in an S formation from five different points at each sampling site, composited to make a total sample weight of about 2 kg, and transferred to plastic bags. Thus, a minimum of 20 point samples were represented in calculating the average values of soil parameters, as suggested by Mollitor et al. (1980). Soils were air dried under shade and transported to the laboratory at Kathmandu University, Nepal, for further processing and analyses. A part of the air-dried soils was ground manually with wooden blocks and passed through 2-mm mesh for determining important physical and chemical properties.

## Soil Analysis

Soil BD was determined by the core method (Blake and Harte, 1986). Soil pH was determined with a pH electrode at soil /water ratio of 1:1 (w/w) (McLean, 1982). The SOC concentration was determined by the dry combustion method using oven-dry soil samples (Nelson and Sommers, 1982). Soil texture was determined using the hydrometer method (Gee and Bauder, 1986). Total N was determined by the Kjeldahl digestion–distillation method (Bremner and Mulvaney, 1982), available P with a modified version of Olsen's method (Olsen and Sommer, 1982), and available K and cation exchange capacity (CEC) by the $NH_4OAc$ method (Thomas, 1982). Ultrasound was used to separate soil particles to determine the particle-associated SOC. Particle-associated SOC was determined by auto CN analyzer (Vario Max CN Macro Elemental Analyser, Elementar Analysensysteme GmbH, Hanau, Germany).

## Water-Stable Aggregates

The size distribution of aggregates was measured by a wet sieving method (Yoder, 1936). Bulk soil samples were passed through 8- and 5-mm mesh to collect soil aggregates between 5- and 8-mm size. One hundred grams of aggregates was placed in the first sieve of a nest of sieves with 5-, 2-, 0.5-, and 0.25-mm openings and slowly wetted in tap water for about 20 min. The water level in the container was adjusted so that the base of the top sieve just touched the water and aggregates were allowed to saturate by capillary rise of water. Then the nest was oscillated manually in the water at 60 oscillations $min^{-1}$ for 2 min. Aggregates retained in the sieves were transferred to beakers using tap water. The weight of each aggregate fraction was recorded after drying at 105°C for 24 h. The data were analyzed to compute WSA (Kemper and Rosenau, 1986), the geometric mean diameter, and the mean weight diameter (Youker and McGuinness, 1956).

Soil organic C associated with different aggregate size fractions was also determined by the dry combustion method. To reduce the sample number, aggregates of sizes 0.25 to 0.5 and <0.25 mm were pooled together to cope with the facilities available and time and economic constraints in the determination of the associated SOC concentration.

## Soil Particle-Size Fractionation

Composite samples of about 100 g were prepared for surface and subsurface layers, pooling equal amounts (by weight) of air-dried and sieved (2-mm mesh) bulk soil

**Table 2. Basic parameters of soils used in the experiment.†**

| Land use‡ | BD | SOC | pH (1:1 soil/water) | TN | P | K | CEC |
|---|---|---|---|---|---|---|---|
| | g cm$^{-3}$ | g kg$^{-1}$ | | g kg$^{-1}$ | mg kg$^{-1}$ | mg kg$^{-1}$ | cmol kg$^{-1}$ |
| | | | | 0–10 cm soil depth | | | |
| *Bari* | 1.2 (0.1) AB§ | 18.6 (2.7) | 6.2 (0.3) | 0.6 (0.1) C | 23.5 (15) | 203.4 (74.0) | 15.8 (2.1) |
| *Khet* | 1.2 (0.0) AB | 18.2 (2.1) | 5.5 (0.1) | 1.6 (0.2) A | 13.0 (5.1) | 99.6 (28.7) | 16.1 (4.2) |
| DF | 1.3 (0.0) A | 18.1 (4.5) | 6.1 (0.1) | 0.8 (0.1) C | 10.2 (1.6) | 192.5 (72.5) | 19.6 (2.4) |
| DS | 1.2 (0.1) AB | 16.9 (1.0) | 5.8 (0.1) | 1.3 (0.2) B | 5.6 (1.0) | 127.7 (26.3) | 11.3 (1.3) |
| PS | 1.3 (0.1) AB | 12.9 (1.2) | 5.8 (0.1) | 0.6 (0.1) C | 14.7 (6.3) | 330.7 (74.4) | 14.5 (0.5) |
| SC | 0.9 (0.0) B | 17.8 (1.4) | 5.9 (0.1) | 0.6 (0.1) C | 9.5 (1.7) | 184.6 (22.2) | 15.5 (1.9) |
| SPS | 1.0 (0.1) AB | 15.3 (1.1) | 6.0 (0.1) | 0.5 (0.1) C | 8.1 (1.8) | 159.0 (27.9) | 13.4 (0.7) |
| | | NS | NS | | NS | NS | NS |
| | | | | 10–20 cm soil depth | | | |
| *Bari* | 1.4 (0.1) A | 17.9 (2.5) | 6.2 (0.3) AB | 1.3 (0.3) | 19.0 (13.1) | 162.9 (47.9) | 16.2 (2.1) AB |
| *Khet* | 1.2 (0.0) AB | 15.8 (2.0) | 5.7 (0.2) B | 1.4 (0.2) | 10.5 (4.5) | 114.0 (29.5) | 16.1 (4.4) AB |
| DF | 1.4 (0.1) A | 14.1 (1.1) | 6.6 (0.3) A | 1.0 (0.1) | 8.8 (1.7) | 145.3 (50.5) | 23.5 (1.2) A |
| DS | 1.1 (0.1) AB | 16.4 (0.8) | 5.9 (0.1) AB | 0.8 (0.1) | 5.2 (0.7) | 87.0 (7.9) | 11.6 (1.9) B |
| PS | 1.1 (0.1) AB | 12.6 (1.0) | 5.8 (0.1) B | 0.7 (0.1) | 18.3 (7.8) | 279.9 (121.4) | 15.5 (0.6) AB |
| SC | 1.0 (0.1) B | 16.0 (1.2) | 5.9 (0.2) AB | 1.3 (0.2) | 7.0 (0.9) | 150.7 (20.2) | 16.0 (2.5) AB |
| SPS | 1.0 (0.1) B | 13.4 (0.5) | 5.9 (0.1) AB | 1.1 (0.3) | 8.1 (1.7) | 130.6 (25.4) | 11.4 (1.3) B |
| | | NS | | NS | NS | NS | |

† BD, bulk density; SOC, soil organic carbon; TN, total nitrogen; P, available phosphorus; K, extractable potassium; CEC, cation exchange capacity.

‡ *Bari*, Rainfed upland; *khet*, irrigated lowland; DF, degraded forest and shrub land; DS, dense *Shorea* forest; PS, pine–*Shorea* forest; SC, *Schima–Castanopsis* forest; SPS, *Schima*–pine–*Shorea* forest.

§ Mean values followed by standard errors in the parentheses; values with different letters are significantly different. NS = not significant at $P < 0.05$ (Student–Newman–Kuels $\alpha = 0.05$).

samples for each land use type. Two pseudo-replications of composite soil samples of 20 g were put in a plastic jar and dispersed ultrasonically at a soil/water ratio of 1:5 (w/w) with energy of 100 J mL$^{-1}$ using a probe-type sonicator. The sand fraction (>53 μm) was separated by wet sieving, and the remaining material was further sonicated and transferred to a settling mechanism to separate out the silt fraction by sedimentation. After 8 h of settling from a 10-cm-high suspension column, the clay suspension was siphoned off into a bucket and the process was repeated twice by adding deionized water, stirring vigorously, allowing it to settle down for 8 h, and siphoning the clay suspension into a container. The remaining settled silt was transferred to a beaker from the settling container. Clay particles were flocculated by adding a flocculating agent ($MgCl_2$) to the bucket. Flocculated clay particles were separated by repeated centrifugation, keeping the slurry in the centrifuging bottles. All sand, silt, and clay particles were dried at 40°C for 72 h, and were ground with a mortar and pestle for analyses of total organic C and N concentrations. Total SOC and N concentrations were analyzed with a Vario Max CN Macro Elemental Analyser (Elementar Analysensysteme GmbH).

## Calculation and Statistical Analysis

Aggregates were categorized as macro (2.0–5.0 mm), meso (0.5–2.0 mm), and micro (<0.5 mm), and their relative proportions in the sample were expressed as a percentage of the total sample. Soil organic C and N associated with the aggregates and particle size fractions were expressed as grams per kilogram and data were analyzed using SAS software (SAS Institute, 2004). The effects of land use, depth, and other soil parameters were analyzed by the general linear model procedure (PROC GLM). Multiple comparison of means for each class variable was performed using the Student–Newman–Kuels test (SNK) at significance level ($\alpha$) = 0.05.

# RESULTS AND DISCUSSION

## Soil Properties

Soil BD was significantly higher under DF than other land uses in both surface (1.3 g cm$^{-3}$) and subsurface (1.4 g cm$^{-3}$) layers (Table 2). Among cultivated fields, soil BD was similar in surface layers of both *khet* and *bari* but *bari* soil had higher BD in the subsurface than the surface layer. These results are in accord with those of Sahani and Behera (2001) and Hajabbasi et al. (1997), who also reported higher BD in deforested and continuously cultivated lands. The trend of increase in BD with increasing soil depth is in agreement with the results reported by Shrestha et al. (2004). The mean SOC concentration ranged from 12.9 to 18.6 g kg$^{-1}$ and decreased with increasing depth for each land use. In the surface layer, soil under mixed pine forests contained lower SOC concentration than broadleaf forests; however, the SOC concentration did not differ significantly among different land uses (SNK, $\alpha = 0.05$).

Mean soil pH ranged from 5.5 to 6.2 in the surface layer and from 5.7 to 6.6 in the subsurface layer. Soils under *khet* land use were slightly more acidic than under *bari*, indicating the effect of $NH_4$ and urea fertilizer use in *khet* land. Total organic N (TN) concentration was low in all soils regardless of land use. *Bari* soil contained higher concentrations of P and K than other land uses, presumably due to higher input of organic manure and chemical fertilizers (Awasthi et al., 2005). The CEC was as low as 11 cmol kg$^{-1}$ in SPS forest, and it was highest in DF (20 and 23.5 cmol kg$^{-1}$ in surface and subsurface soils, respectively). The CEC was generally higher in subsurface than surface layers.

The texture of all soil samples was sandy loam with varying amounts of sand, silt, and clay (Table 3). Sand content was significantly higher in SPS forest (716 ± 20 g kg$^{-1}$) but silt content was higher in cultivated lands (*khet* 318 ± 28 g kg$^{-1}$, *bari* 312 ± 51 g kg$^{-1}$) in surface layers than subsurface layers. Clay content varied from 81 to 200 g kg$^{-1}$ but did not statistically differ.

## Size Distribution and Water Stability of Aggregates

Land use had a significant effect ($P < 0.001$) on the aggregate size distribution and the water stability of aggregates. Forest soils had more macro- than microaggregates, while cultivated soils had a greater proportion of micro- than macroaggregates (Table 4). Among forest soils, SPS forest contained a significantly higher amount of

**Table 3. Soil particle size distribution in 0- to 20-cm soil depths under different land uses.**

| Land use† | Particle size distribution | | | | | |
|---|---|---|---|---|---|---|
| | 0–10-cm depth | | | 10–20-cm depth | | |
| | Sand | Silt | Clay | Sand | Silt | Clay |
| | g kg$^{-1}$ | | | | | |
| *Bari* | 488 (55) C‡ | 312 (51) A | 200 (63) | 452 (73) B | 304 (35) A | 243 (83) |
| *Khet* | 555 (34) BC | 318 (28) A | 127 (7) | 573 (47) AB | 296 (13) A | 131 (42) |
| DF | 654 (24) AB | 194 (10) B | 152 (14) | 631 (34) A | 200 (17) B | 168 (20) |
| DS | 585 (47) ABC | 222 (18) AB | 193 (29) | 664 (44) A | 181 (32) B | 156 (12) |
| PS | 661 (34) AB | 171 (18) B | 168 (17) | 669 (29) A | 184 (14) B | 147 (17) |
| SC | 694 (16) AB | 226 (11) AB | 81 (8) | 686 (22) A | 242 (12) AB | 72 (10) |
| SPS | 716 (20) A | 178 (10) B | 106 (10) NS | 711 (27) A | 171 (8) B | 118 (22) NS |

† *Bari*, Rainfed upland; *khet*, irrigated lowland; DF, degraded forest and shrub land; DS, dense *Shorea* forest; PS, pine–*Shorea* forest; SC, *Schima–Castanopsis* forest; SPS, *Schima*–pine–*Shorea* forest.

‡ Mean values followed by standard errors in parentheses; values with different letters are significantly different, NS = not significant at $P < 0.05$ (Student–Newman–Kuels $\alpha = 0.05$).

macroaggregates in surface ($P < 0.001$) and subsurface ($P < 0.01$) layers than other forest types. Despite the similar SOC concentration in broadleaf forests and cultivated soils, the higher proportion of macroaggregates in forest than in cultivated soils indicated adverse effects of cultivation on soil aggregation. The presence of leaf litter in the forest floor had a mulching effect, and contributed to the replenishment of SOM as well as provided better habitats for soil meso- and microfauna and -flora, which enhance soil aggregation (Blanco-Canqui and Lal, 2004). In contrast, crop residues are usually harvested from the cultivated fields for livestock feed and other purposes and hence are not directly returned to the soil. In addition to frequent tillage and other agricultural operations, the use of agrochemicals (Kansakar et al., 2002) tends to reduce the activity of soil fauna, causing adverse effects on soil aggregation. Furthermore, the SOM that binds microaggregates to form macroaggregates is a labile fraction and is highly sensitive to land use change and cultivation (Ashagrie et al., 2005). Both cultivated soils (*khet* and *bari*) contained a higher amount of micro- than macroaggregates due to disturbance by cultivation. Moreover, fewer macroaggregates in *khet* soil than in other soils were probably due to slaking on rapid immersion in water and puddling during cultivation. The slaking of aggregates depends on a range of parameters, however, such as texture, clay mineralogy, SOM concentration, and the degree and strength of aggregates. In Brazil, Caron et al. (1996) reported that cultivation increased aggregate slaking compared with uncultivated soils under forest.

Water stability of soil aggregates was also significantly affected by land use ($P < 0.001$). Multiple comparison of means (SNK, $\alpha = 0.05$) shows that aggregates in forest soils were more stable than those in cultivated soils (Table 5). Forest soils receive more litter biomass than cultivated soils (Hairiah et al., 2006), which affected aggregation and stability. The amount of plant residues and the degree of SOM decomposition are vital factors in the formation and stabilization of aggregate structure (Blanco-Canqui and Lal, 2004). Despite the similar concentrations of SOC, soil aggregates under mixed SPS forest were more stable in both layers than those in other forest soils (Table 5). It is difficult at this stage to provide a plausible explanation for this result, but we hypothesize that the differences in metal oxide content (Wolfgang and Martin, 1997) and soil water repellency (hydrophobicity) across soils under different land uses and forests sites (Doerr et al., 1998) may be the reason. Hydrophobicity is widespread in forest soils and usually higher under pine forest, and increases aggregate stability (Buczko et al., 2006; Mataix-Solera and Doerr, 2004). The second highest aggregate stability, under SC forest, reflected the role of plant roots and hyphae (Blanco-Canqui and Lal, 2004). The comparatively low aggregate stability of DF reflected the effect of livestock trampling on soil degradation (Conant and Paustian, 2002; Hall and Lamont, 2003).

Among the cultivated soils, aggregates in *bari* soil were more stable than those in *khet* soils. The SOC concentrations and soil texture probably influenced aggregate stability. The magnitude of soil disturbance and the amount of residue incorporated into the soil impact aggregates and the associated C pool (Blanco-Canqui and Lal, 2004). *Bari* soils, being in the proximity of farmhouses, receive much more organic manure than *khet* soils (Pilbeam et al., 2000; Neupane and Thapa, 2001), and this may have influenced the aggregate stability. Lowland soils have greater disturbance due to deliberate puddling and destruction of structure for paddy cultivation (Bajracharya, 2001).

**Table 4. Water-stable aggregate size distribution for different land uses.**

| Depth | Land use† | Aggregate size distribution | | |
|---|---|---|---|---|
| | | 2.0–5.0 mm | 0.5–2.0 mm | <0.5 mm |
| cm | | % | | |
| 0–10 | *Bari* | 15.1 (3.6) Bb‡ | 8.1 (0.8) ABb | 62.5 (4.8) Aa |
| | *Khet* | 11.7 (4.1) Bb | 5.7 (1.2) Bb | 56.1 (4.1) Aa |
| | DF | 46.5 (10.0) Aa | 8.8 (0.8) ABb | 35.4 (9.4) ABa |
| | DS | 44.3 (9.7) Aa | 8.6 (0.7) ABb | 41.6 (9.7) ABa |
| | PS | 40.5 (2.3) Aa | 15.2 (4.5) Ab | 34.6 (5.7) ABa |
| | SC | 56.2 (7.7) Aa | 13.3 (1.9) ABb | 24.8 (6.8) Bb |
| | SPS | 70.0 (9.6) Aa | 9.1 (0.6) ABb | 16.4 (9.5) Bb |
| 10–20 | *Bari* | 11.5 (7.0) Bb | 5.3 (1.1) Bb | 69.1 (6.3) Aa |
| | *Khet* | 13.3 (5.0) Bb | 6.3 (1.5) Bb | 50.3 (4.3) ABa |
| | DF | 30.9 (8.3) ABa | 9.1 (1.8) ABb | 46.7 (8.0) ABa |
| | DS | 36.6 (8.0) ABa | 9.0 (1.5) ABb | 44.4 (7.3) ABa |
| | PS | 38.7 (6.5) ABa | 12.9 (1.8) Ab | 33.7 (6.1) Ba |
| | SC | 36.7 (6.5) ABa | 13.2 (0.4) Ab | 45.6 (7.1) ABa |
| | SPS | 55.6 (12.5) Aa | 8.3 (0.1) ABb | 28.8 (11.6) Bab |

† *Bari*, Rainfed upland; *khet*, irrigated lowland; DF, degraded forest and shrub land; DS, dense *Shorea* forest; PS, pine–*Shorea* forest; SC, *Schima–Castanopsis* forest; SPS, *Schima*–pine–*Shorea* forest.

‡ Mean values followed by standard errors in parentheses; values with the same uppercase letters for land use type and lowercase letters for aggregate size class are not significantly different at $P < 0.05$ (Student–Newman–Kuels $\alpha = 0.05$).

## Carbon Associated with Aggregate Size Fractions

Land use had a significant effect on the SOC concentrations observed in different aggregate size classes ($P < 0.001$). In the surface layer, mesoaggregates (0.5–2.0 mm) contained higher SOC concentrations than macro- and microaggregates in both types of cultivated soils. Macroaggregates in the surface layer of cultivated soils had higher SOC concentrations than those in the forest soils (Table 6). The SOC concentration varied significantly, with a range of 8.3 to 20.9 g kg$^{-1}$ in macroaggregates and 13.4

Table 5. Land use and management effects on soil aggregation and stability.

| Soil depth | Land use† | Water-stable aggregates | Mean weight diameter | Geometric mean diameter |
|---|---|---|---|---|
| cm | | % | mm | mm |
| | *Bari* | 86 (3) b‡ | 3.0 (0.1) b | 0.8 (0.3) b |
| | *Khet* | 74 (2) c | 2.6 (0.1) c | 0.8 (0.3) b |
| | DF | 91 (3) ab | 3.2 (0.1) ab | 1.1 (0.7) ab |
| 0–10 | DS | 95 (1) a | 3.3 (0.0) a | 1.0 (1.1) ab |
| | PS | 90 (5) ab | 3.2 (0.1) ab | 1.0 (0.4) ab |
| | SC | 94 (3) a | 3.3 (0.0) a | 1.2 (1.0) a |
| | SPS | 96 (1) a | 3.3 (0.1) a | 1.4 (1.0) a |
| | *Bari* | 86 (7) a | 3.0 (0.1) a | 0.7 (0.6) b |
| | *Khet* | 70 (7) b | 2.5 (0.1) b | 0.8 (0.2) ab |
| | DF | 87 (2) a | 3.0 (0.1) a | 0.9 (0.6) ab |
| 10–20 | DS | 90 (10) a | 3.2 (0.1) a | 1.0 (0.7) ab |
| | PS | 85 (8) a | 3.0 (0.1) a | 1.0 (0.6) ab |
| | SC | 96 (7) a | 3.3 (0.1) a | 1.0 (0.6) ab |
| | SPS | 93 (4) a | 3.3 (0.1) a | 1.2 (1.1) a |

† *Bari*, Rainfed upland; *khet*, irrigated lowland; DF, degraded forest and shrub land; DS, dense *Shorea* forest; PS, pine–*Shorea* forest; SC, *Schima*–*Castanopsis* forest; SPS, *Schima*–pine–*Shorea* forest.

‡ Mean values followed by standard errors in parentheses; values with the same letters are not significantly different among different land uses at $P < 0.05$ (Student–Newman–Kuels $\alpha = 0.05$).

Table 6. Soil organic C content in water-stable aggregates in different aggregate size classes of soil from different land uses.

| Soil depth | Land use† | Soil organic C content 2.0–5.0 mm | 0.5–2.0 mm | <0.5 mm |
|---|---|---|---|---|
| | | g kg$^{-1}$ | | |
| cm | | | | |
| | *Bari* | 20.9 (1.7)Aa‡ | 24.3 (1.7)ABa | 22.1 (2.9)Aa |
| | *Khet* | 20.9 (1.3)Ab | 27.8 (2.2)Aa | 19.3 (1.1)Ab |
| | DF | 13.1 (1.1)BCb | 16.5 (0.8)CDa | 18.3 (0.7)Aa |
| 0–10 | DS | 15.3 (1.0)Bb | 20.8 (2.0)BCa | 16.7 (0.8)Aab |
| | PS | 10.5 (0.8)CDb | 12.8 (1.4)Dab | 16.2 (1.4)Aa |
| | SC | 19.7 (0.5)Aa | 20.2 (1.0)BCa | 17.0 (2.0)Aa |
| | SPS | 8.3 (1.0)Db | 13.4 (2.6)Dab | 19.0 (3.0)Aa |
| | *Bari* | 15.5 (4.2)ABa | 21.6 (3.0)Aa | 21.7 (3.1)Aa |
| | *Khet* | 10.6 (1.0)ABb | 18.1 (2.0)ABa | 18.2 (1.8)Aa |
| | DF | 13.6 (1.1)ABa | 15.3 (1.7)ABa | 18.4 (3.5)Aa |
| 10–20 | DS | 11.1 (1.9)ABb | 18.6 (1.3)ABa | 16.7 (1.1)Aa |
| | PS | 10.7 (1.0)ABa | 11.6 (1.3)Ba | 14.8 (1.4)Aa |
| | SC | 18.2 (1.2)Aa | 20.2 (1.0)Aa | 16.5 (1.5)Aa |
| | SPS | 7.7 (1.3)Ba | 10.4 (2.1)Bab | 15.2 (1.3)Aa |

† *Bari*, Rainfed upland; *khet*, irrigated lowland; DF, degraded forest and shrub land; DS, dense *Shorea* forest; PS, pine–*Shorea* forest; SC, *Schima*–*Castanopsis* forest; SPS, *Schima*–pine–*Shorea* forest.

‡ Means with standard error in parentheses; values followed by the same uppercase letter for land use and lowercase letter for aggregate classes are not significantly different at P < 0.05 (Student–Newman–Kuels $\alpha = 0.05$).

to 24.3 g kg$^{-1}$ in mesoaggregates. The variation in SOC concentration in microaggregates (17.0–22.1 g kg$^{-1}$) did not differ significantly among land uses. The SOC concentration in aggregates appeared to decrease with increase in depth, but this trend was not always statistically significant. Surface soils under SPS forest contained the lowest SOC concentration in macroaggregates and the highest (but not statistically) in microaggregates compared with the soil under other forests. The higher SOC concentration in microaggregates could explain the relatively high aggregate stability observed in these soils.

Figure 3 presents the proportion of total SOC shared by different aggregate size fractions. The share of SOC in cultivated soil was significantly ($P < 0.001$) dominated by microaggregates, while in forest soils by micro- or macroaggregates ($P < 0.05$). The contribution of the mesoaggregate size class in SOC was not significant in any of the land uses. The difference in SOC concentration in bulk soil and the sum of SOC in three aggregates in 100 g of soil was calculated (Table 7), and was found to be statistically not significant; however, the sum of SOC in aggregate size classes was more than SOC in bulk soil in cultivated soils and SC forest, but it was slightly less in the case of the other forests. Such slight differences are apparently due to methodological and inherent soil variability.

## Soil Particle Size Distribution and Particle-Size-Associated Soil Organic Carbon and Nitrogen

The data in Table 8 present the proportional distribution of primary particles obtained through the ultrasonic dispersion method and SOC associated with primary particles for soils under different land use systems. In the surface layer (0–10 cm), all forest soils except DS forest had quantitatively (not statistically) higher amounts of sand particles but lower amounts of silt and clay particles than cultivated soils; however, the amount of clay particles was highest in *bari* soil ($P < 0.001$). In the subsurface layer (10–20 cm), the PS forest soil had the highest amount of sand and SC forest had the least amount of clay particles compared with soils under other land uses. Despite the lowest clay content,

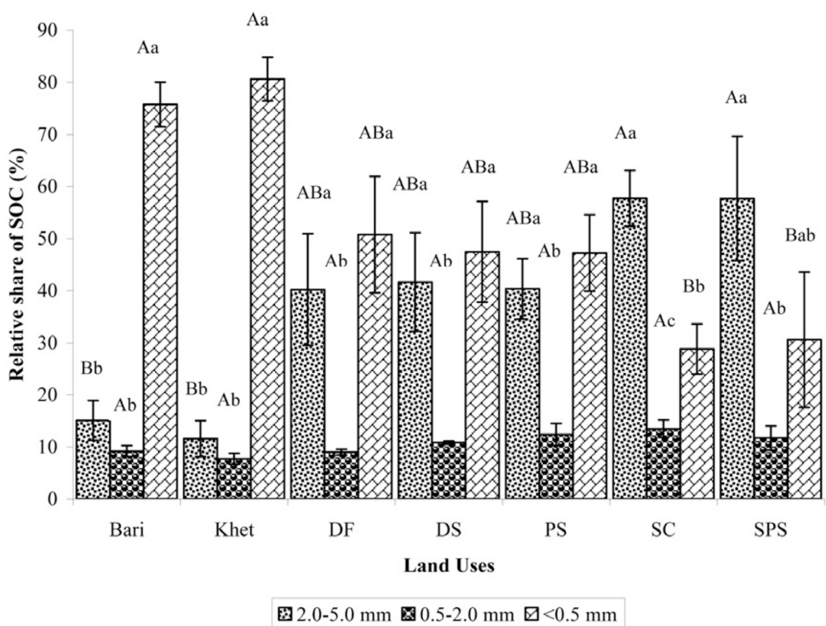


**Fig. 3. Relative share of soil organic carbon (SOC) in soil by different aggregate size fractions under different land uses (*bari*, rainfed upland; *khet*, irrigated lowland; DF, degraded forest and shrub land; DS, dense *Shorea* forest; PS, pine–*Shorea* forest; SC, *Schima–Castanopsis* forest; SPS, *Schima*–pine–*Shorea* forest). Mean ± SE; values with different letters, uppercase for land uses and lowercase for aggregate size classes, are significantly different at $P < 0.05$ (Student–Newman–Kuels $\alpha = 0.05$).**

**Table 7. Soil organic carbon (SOC) balance in 100 g of soil.**

| Soil depth | Land use† | Total SOC in bulk soil | Total SOC in all aggregate sizes | SOC balance |
|---|---|---|---|---|
| cm | | g | | |
| 0–10 | *Bari* | 1.9 (0.3)‡ | 2.2 (0.3) A | –0.3 (0.1) |
| | *Khet* | 1.8 (0.2) | 2.0 (0.1) A | –0.2 (0.2) |
| | DF | 1.8 (0.5) | 1.6 (0.0) AB | 0.2 (0.4) |
| | DS | 1.7 (0.1) | 1.6 (0.1) AB | 0.1 (0.0) |
| | PS | 1.3 (0.1) | 1.3 (0.1) BC | 0.0 (0.1) |
| | SC | 1.8 (0.1) | 1.8 (0.1) AB | –0.1 (0.0) |
| | SPS | 1.5 (0.1) | 1.0 (0.1) C | 0.5 (0.1) |
| | | NS | | NS |
| 10–20 | *Bari* | 1.8 (0.3) | 2.1 (0.3) A | –0.4 (0.1) B |
| | *Khet* | 1.6 (0.2) | 1.7 (0.2) AB | –0.1 (0.1) AB |
| | DF | 1.4 (0.1) | 1.8 (0.3) AB | –0.4 (0.2) B |
| | DS | 1.6 (0.1) | 1.5 (0.1) AB | 0.1 (0.1) AB |
| | PS | 1.3 (0.1) | 1.2 (0.1) AB | 0.0 (0.2) AB |
| | SC | 1.6 (0.1) | 1.8 (0.1) AB | –0.1 (0.0) AB |
| | SPS | 1.3 (0.0) | 1.0 (0.2) B | 0.3 (0.2) A |
| | | NS | | |

† *Bari*, Rainfed upland; *khet*, irrigated lowland; DF, degraded forest and shrub land; DS, dense *Shorea* forest; PS, pine–*Shorea* forest; SC, *Schima*–*Castanopsis* forest; SPS, *Schima*–pine–*Shorea* forest.

‡ Mean with standard error in parentheses followed by different letters for land use are significantly different and NS = not significant for land use at $P < 0.05$ (Student–Newman–Kuels $\alpha = 0.05$).

the SOC associated with the clay fraction was the highest (43.7 ± 4.1 g $kg^{-1}$) in SC forest compared with the other forest soils (Table 8). The clay-associated C in forest soil was in the order of SC > DS > SPS > DF > PS. This trend may be attributed to differences in input of leaf litter types under different forests. Leaf litter from broadleaf trees decomposes more rapidly than that from pine needles (Kavvadias et al., 2001), and this may have contributed to the higher SOC concentration associated with the clay fraction of SC forest compared with other forests.

A higher correlation was observed between texture and SOC concentration when SOC was plotted as a function of silt plus clay content than clay content alone (Fig. 4), indicating the difficulty in separation of silt and clay fractions in the soil. The result suggests that clay content alone cannot determine the SOC retained in the soil. Similar results were reported by Zinn et al. (2005), who observed a direct and linear relationship between SOC concentration and the combined clay plus silt content in some Brazilian soils. Furthermore, Neufeldt et al. (2002) reported that stabilization of organic compounds differed by surface stabilization of clay contents in different land uses.

There was only a weak linear relationship between particle size content and the associated SOC concentrations in the sand and silt fractions, but a significant negative linear relationship ($P = 0.02$) was observed between clay content and clay-associated SOC concentrations. Figure 5 shows that the quadratic function as a better fit to the data ($P = 0.002$). Zinn (2005) reported that the same specific particle size fraction had a higher concentration of SOC if the yield of that fraction was less and a lower SOC con-

**Table 8. Distribution of particle sizes and soil organic C (SOC) content, N content, and C/N ratio associated with sand, silt, and clay fractions from soils under different land uses.**

| Soil depth | Particle size | Land use† | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | *Bari* | *Khet* | DF | DS | PS | SC | SPS |
| cm | | | | | | | | |
| | | | | | Particle size distribution, g $kg^{-1}$ | | | |
| 0–10 | Sand | 535 (0) a‡ | 551 (93) a | 723 (6) a | 639 (132) a | 834 (16) a | 787 (34) a | 779 (31) a |
| | Silt | 234 (0) a | 332 (84) a | 177 (9) a | 229 (59) a | 111 (1) a | 160 (4) a | 160 (24) a |
| | Clay | 206 (0) a | 100 (8) b | 92 (7) b | 103 (4) b | 61 (1) b | 28 (3) c | 75 (33) bc |
| 10–20 | Sand | 518 (2) a | 627 (14) ab | 708 (21) a | 610 (77) ab | 791 (3) a | 742 (15) a | 763 (5) a |
| | Silt | 278 (2) a | 234 (5) ab | 178 (10) ab | 229 (59) ab | 119 (6) b | 191 (5) ab | 153 (12) ab |
| | Clay | 180 (14) a | 126 (19) b | 81 (8) bc | 95 (3) bc | 95 (18) bc | 49 (21) c | 70 (3) bc |
| | | | | | SOC content, g $kg^{-1}$ | | | |
| 0–10 | Sand | 2.9 (0.2) a | 3.6 (1.4) a | 4.3 (1) a | 3.5( 0.2) a | 1.8 (0.2) a | 5.8 (0.9) a | 3.5 (1.5) a |
| | Silt | 11.1 (3.1) ab | 12.3 (0.6) ab | 7.7 (0.8) b | 10.9 (1.4) ab | 6.2 (1.0) b | 21.9 (3.6) a | 13.0 (2.7) ab |
| | Clay | 16.5 (1.7) b | 22.2 (1.0) b | 13.9 (1.8) b | 17.0 (2.4) b | 12.4 (1.7) b | 43.7 (4.1) a | 15.5 (3.2) b |
| 10–20 | Sand | 2.7 (1) a | 3.5 (0.2) a | 2.4 (0.5) a | 3.2 (0.0) a | 1.5 (0.1) a | 3.6 (0.7) a | 3.6 (1.2) a |
| | Silt | 9.7 (2.1) ab | 11.9 (1.1) ab | 7.6 (1.2) b | 10.3 (1.6) ab | 6.1 (0.4) b | 20.6 (3.8) a | 13.1 (3.6) ab |
| | Clay | 16.0 (1.6) bc | 22.9 (0.3) b | 14.1 (1.9) bc | 17.5 (1.2) bc | 12.2 (1.1) c | 44.3 (2.5) a | 16.2 (3.3) bc |
| | | | | | N content, g $kg^{-1}$ | | | |
| 0–10 | Sand | 0.5 (0.0) a | 0.5 (0.2) a | 0.5 (0.1) a | 0.4 (0.1) a | 0.3 (0.0) a | 0.7 (0.2) a | 0.4 (0.2) a |
| | Silt | 1.2 (0.4) ab | 1.3 (0.0) ab | 0.7 (0.1) b | 1.0 (0.1) ab | 0.6 (0.1) b | 2.2 (0.4) a | 1.2 (0.3) ab |
| | Clay | 2.2 (0.2) bc | 2.8 (0.1) b | 1.5 (0.2) c | 2.0 (0.3) bc | 1.5 (0.2) c | 4.1 (0.1) a | 1.7 (0.3) c |
| 10–20 | Sand | 0.3 (0.1) a | 0.3 (0.0) a | 0.2 (0.0) a | 0.3 (0.0) a | 0.2 (0.0) a | 0.3 (0.1) a | 0.2 (0.1) a |
| | Silt | 0.9 (0.3) a | 1.0 (0.1) a | 0.6 (0.1) a | 0.8 (0.1) a | 0.5 (0.0) a | 1.8 (0.5) a | 1.0 (0.4) a |
| | Clay | 2.0 (0.2) c | 2.7 (0.1) b | 1.6 (0.2) c | 1.9 (0.2) c | 1.4 (0.1) c | 4.6 (0.2) a | 1.7 (0.3) c |
| | | | | | C/N ratio | | | |
| 0–10 | Sand | 6.3 (0.4) a | 7.6 (0.0) a | 8.3 (1.0) a | 8.4 (0.8) a | 5.4 (0.5) a | 8.6 (0.6) a | 8.4 (0.2) a |
| | Silt | 9.7 (0.6) c | 9.6 (0.1) c | 11.8 (0.3) a | 11.4 (0.1) abc | 10.1 (0.2) bc | 9.8 (0.1) bc | 11.3 (0.7) ab |
| | Clay | 7.7 (0.0) b | 8.0 (0.2) b | 9.0 (0.1) b | 8.8 (0.2) b | 8.6 (0.2) b | 10.7 (1.1) a | 9.2 (0.3) b |
| 10–20 | Sand | 9.6 (0.4) b | 11.4 (0.0) b | 12.0 (0.6) b | 12.8 (1.6) b | 7.9 (1.2) b | 11.4 (0.8) b | 15.6 (1.0) a |
| | Silt | 10.8 (0.9) a | 11.6 (0.0) a | 12.8 (0.0) a | 13.8 (0.6) a | 11.6 (0.1) a | 11.6 (1.0) a | 14.3 (1.6) a |
| | Clay | 8.2 (0.1) c | 8.3 (0.1) c | 8.7 (0.1) b | 9.2 (0.1) b | 8.5 (0.4) bc | 9.7 (0.2) a | 9.7 (0.2) a |

† *Bari*, Rainfed upland; *khet*, irrigated lowland; DF, degraded forest and shrub land; DS, dense *Shorea* forest; PS, pine–*Shorea* forest; SC, *Schima*–*Castanopsis* forest; SPS, *Schima*–pine–*Shorea* forest.

‡ Mean values with standard error in parentheses followed by the same letter for land use are not significantly different at $P < 0.05$ (Student–Newman–Kuels $\alpha = 0.05$).

centration if the yield was high and he termed it a "dilution effect." The data from the present study show that the dilution effect was pronounced in the clay fraction. For example, undisturbed SC forest had a relatively low amount of clay but the clay fraction was richer in associated SOC than soils under other land use systems, while *bari* soil had higher clay contents but the associated SOC concentration was low (Table 8).

The C/N ratio was higher in the silt fraction than in the clay and sand fractions for the majority of soils. In general, the coarser fractions contain undecomposed or partially decomposed SOM with a higher C/N ratio than the finer fractions; however, the results of the present study showed that the sand fraction had lower C/N ratios than the silt and clay fractions. The underlying mechanism for such a trend is not understood. Further investigation into the speciation of SOC in the soils, including particulate organic C, may be needed to elucidate the processes involved.

The sand-associated SOC was highest ($5.8 \pm 0.9$ g kg$^{-1}$) in undisturbed natural SC forest but it was not statistically different from other land uses. The sand-associated SOC concentration was only 50% in *bari* soil and 63% in *khet* soil compared with that in the forest soils. These results show that the land use change effect was described by the sand-associated SOC fraction; however, particle-associated SOC also depended on vegetation type and soil management. For example, soil in pine mixed forest showed very low levels of sand-associated SOC, which may be due to slow decomposition of pine needles (Kavvadias et al., 2001). The highest concentration of clay-associated SOC was in SC forest, showing that natural forests are rich in stable SOC as clay-associated SOC has a higher residence time than the sand- or silt-associated fraction (Ashagrie et al., 2005).

The result of land use effects on SOC and soil properties need to be interpreted with caution. The study site is located in a mountainous watershed with varying altitude. Thus, variation reported here may be partly due to the interactive effect of land use and microclimate, and not solely due to land use. Greater spatial coverage (i.e., higher sampling intensity and replicates) along the altitudinal gradients would be needed to generalize these results.

## CONCLUSIONS

Aggregate stability under different land uses was in the order of SPS > DS > SC > DF > PS > *bari* > *khet,* thus showing higher stability and aggregation under forest than agricultural land uses. On the contrary, the aggregate-associated SOC was higher in cultivated soils, indicating the positive effect of fertilizer input. Microaggregates accounted for a higher proportion of SOC in cultivated soils, while in forest soils macroaggregates exhibited a similar trend. The amount of SOC was somewhat higher when it was derived from SOC in the different aggregate size classes than from bulk soil. Soil particles under undisturbed natural forest contained higher amounts of associated SOC concentration. Cultivated soils had higher clay content but lower clay-associated SOC than soil under other land uses, indicating a dilution effect on particle-associated SOC. The SOC associated with the sand fraction was reduced in cultivated soils compared with forest soils, but was very low in the mixed pine forest. The SOC in bulk soil correlated significantly with silt plus clay contents. Higher aggregate-associated SOC in cultivated soils but lower aggregate stability than forest soils indicates a disproportionately higher risk of SOC loss through accelerated runoff and erosion. Thus, a judicious management of cultivated soil is needed for sustainability of soil and water resources, as illustrated in this study of land uses within the Pokhare Khola watershed in Nepal.


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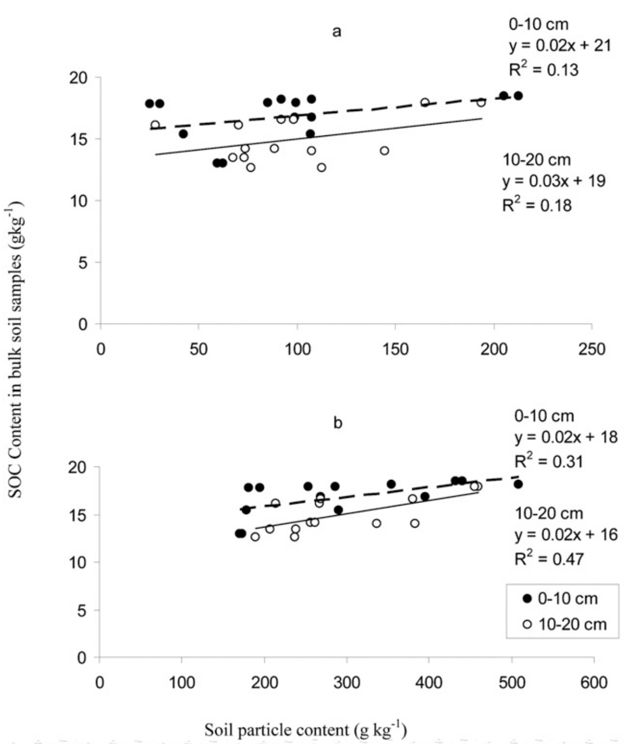


**Fig. 4. Soil organic carbon (SOC) content as a function of (a) clay ($P = 0.065$) and (b) clay plus silt content of soil ($P = 0.002$).**

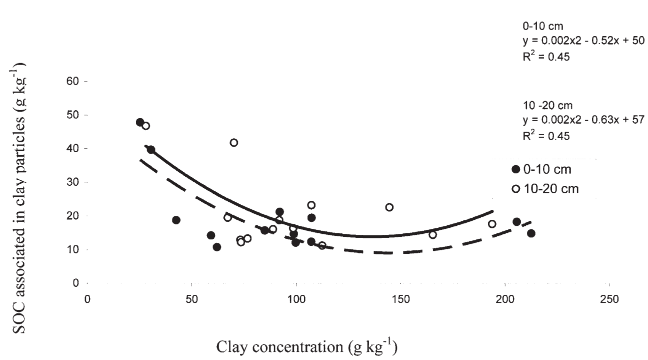


**Fig. 5. Relationship between clay and clay-associated soil organic carbon (SOC) ($P = 0.002$).**

## REFERENCES


Ashagrie, Y., W. Zech, and G. Guggenberger. 2005. Transformation of a *Podocarpus falcatus* dominated natural forest into a monoculture *Eucalyptus globulus* plantation at Munesa, Ethiopia: Soil organic C, N and S dynamics in primary particle and aggregate-size fractions. Agric. Ecosyst. Environ. 106:89–98.

Awasthi, K.D. 2004. Land use change effects on soil degradation, carbon and nutrient stocks and greenhouse gas emission in mountain watersheds. Ph.D. diss. Agric. Univ. of Norway, Ås.

Awasthi, K.D., B.R. Singh and B.K. Sitaula. 2005. Profile carbon and nutrient levels and management effect on soil quality indicators in the Mardi watershed of Nepal. Acta Agric. Scand. B 55:192–204.

Bajracharya, R.M. 2001. Land preparation: An integral part of farming system in the mid-hills of Nepal. Nepal J. Sci. Technol. 3:15–24.

Bajracharya, R.M., R. Lal, and J.M. Kimble. 1998. Soil organic carbon distribution in aggregates and primary particle fractions as influenced by erosion phases and landscape position. p. 353–367. *In* R. Lal et al. (ed.) Soil processes and the carbon cycle. CRC Press, Boca Raton, FL.

Barthes, B., and E. Roose. 2002. Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. Catena 47:133–149.

Bergkamp, G., and J. Jongejans. 1988. The stability of soil aggregates in the middle mountains of Nepal. FGBL Landsc. and Environ. Res. Group, Univ. of Amsterdam, Amsterdam, the Netherlands.

Blake, G.R., and K.H. Harte. 1986. Bulk density. p. 363–375. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. SSSA Book Ser. 5. SSSA, Madison, WI.

Blanco-Canqui, H., and R. Lal. 2004. Mechanisms of carbon sequestration in soil aggregates. Crit. Rev. Plant Sci. 23:481–504.

Boix-Fayos, C., A. Calvo-Cases, A.C. Imeson, and M.D. Soriano-Soto. 2001. Influence of soil properties on the aggregation of some Mediterranean soils and the use of aggregate size and stability as land degradation indicators. Catena 44:47–67.

Bremner, J.M., and C.S. Mulvaney. 1982. Nitrogen—Total. p. 595–624. *In* A.L. Page (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Bronick, C.J., and R. Lal. 2005. Manuring and rotation effects on soil organic carbon concentration for different aggregate size fractions on two soils in northeastern Ohio, USA. Soil Tillage Res. 81:239–252.

Buczko, U., O. Bens, and R.F. Huttl. 2006. Water infiltration and hydrophobicity in forest soils of a pine–beech transformation chronosequence. J. Hydrol. 331:383–395.

Caron, J., C.R. Espindola, and D.A. Angers. 1996. Soil structural stability during rapid wetting: Influence of land use on some aggregate properties. Soil Sci. Soc. Am. J. 60:901–908.

Castro Filho, C., A. Lourenco, M.D.F. Guimaraes, and I.C.B. Fonseca. 2002. Aggregate stability under different soil management systems in a red latosol in the state of Parana, Brazil. Soil Tillage Res. 65:45–51.

Central Bureau of Statistics. 2003. Population and environment, a situation analysis of population, cultivated land and basic crop production in Nepal in 2001. Ch 11. *In* Population monograph of Nepal. Vol. 2. Central Bureau of Statistics, Kathmandu.

Cerda, A. 2000. Aggregate stability against water forces under different climates on agriculture land and scrubland in southern Bolivia. Soil Tillage Res. 57:159–166.

Christensen, B.T. 2001. Physical fractionation of soil and structural and functional complexity in organic matter turnover. Eur. J. Soil Sci. 52:345–353.

Conant, R.T., and K. Paustian. 2002. Potential soil carbon sequestration in overgrazed grassland ecosystems. Global Biogeochem. Cycles 16(4):1143, doi:10.1029/2001GB001661.

Doerr, S.H., R.A. Shakesby, and R.P.D. Walsh. 1998. Spatial variability of soil hydrophobicity in fire-prone Eucalyptus and pine forests, Portugal. Soil Sci. 163:313–324.

Gami, S.K., J.K. Ladha, H. Pathak, M.P. Shah, E. Pasuquin, S.P. Pandey, P.R. Hobbs, D. Joshy, and R. Mishra. 2001. Long-term changes in yield and soil fertility in a twenty-year rice–wheat experiment in Nepal. Biol. Fertil. Soils 34:73–78.

Gardner, R., and J. Gerrard. 2001. Soil loss on noncultivated land in the Middle Hills of Nepal. Phys. Geogr. 22:376–393.

Gardner, R.A.M., and A.J. Gerrard. 2003. Runoff and soil erosion on cultivated rainfed terraces in the Middle Hills of Nepal. Appl. Geogr. 23:23–45.

Gee, G.W., and J.W. Bauder. 1986. Particle size analysis. p. 383–411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. SSSA Book Ser. 5. SSSA, Madison, WI.

Hairiah, K., H. Sulistyani, D. Suprayogo, Widianto, P. Pumomosidhi, R.H. Widodo, and M. Van Noordwijk. 2006. Litter layer residence time in forest and coffee agroforestry systems in Sumberjaya, West Lampung. Forest Ecol. Manage. 224:45–57.

Hajabbasi, M.A., A. Jalalian, and H.R. Karimzadeh. 1997. Deforestation effect on soil physical and chemical properties, Lordegan, Iran. Plant Soil 190:301–308.

Hall, K., and N. Lamont. 2003. Zoogeomorphology in the Alpine: Some observations on abiotic–biotic interactions. Geomorphology 55:219–234.

Hao, X., C. Chang, and C.W. Lindewall. 2001. Tillage and crop sequence effect on organic carbon and total nitrogen content in an irrigated Alberta soil. Soil Tillage Res. 62:167–169.

Herrick, J.E., W.G. Whitford, A.G. de Soyza, J.W. Van Zee, K.M. Havstad, C.A. Seybold, and M. Walton. 2001. Field soil aggregate stability kit for soil quality and rangeland health evaluations. Catena 44:27–35.

Government of Nepal. 1989. Master plan for the forestry sector Nepal. Main Report. Ministry of Forests and Soil Conservation, Kathmandu.

Government of Nepal. 1994. Map compiled from 1:50 000 scale aerial photography of 1992. Field verification 1994. Survey Dep., Government of Nepal, Kathmandu.

Ives, J.D. 1987. The theory of Himalayan environmental degradation—Its validity and application challenged by recent research. Mt. Res. Dev. 7:189–199.

Jastro, J.D., and R.M. Miller. 1998. Soil aggregate stabilization and carbon sequestration: Feedback through organomineral associations. p. 207–223. *In* R. Lal et al. (ed.) Soil processes and the carbon cycle. CRC Press, Boca Raton, FL.

Kansakar, V.B.S., N.R. Khanal, and M.L. Ghimire. 2002. Use of pesticide in Nepal. Landschaftsökologie und Umweltforschung 38:90–98.

Kavvadias, V.A., D. Alifragis, A. Tsiontsis, G. Brofas, and G. Stamatelos. 2001. Litterfall, litter accumulation and litter decomposition rates in four forest ecosystems in northern Greece. For. Ecol. Manage. 144:113–127.

Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. p. 425–442. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. SSSA Book Ser. 5. SSSA, Madison WI.

Kettler, T.A., J.W. Doran, and T.L. Gilbert. 2001. Simplified method for soil particle-size determination to accompany soil-quality analyses. Soil Sci. Soc. Am. J. 65:849–852.

Khanna, P.K., B. Ludwig, J. Bauhus, and C. O'Hara. 2001. Assessment and significance of labile organic C pools in forest soils. p. 167–182. *In* R. Lal et al. (ed.) Assessment methods for soil carbon. Lewis Publ., Boca Raton, FL.

Lal, R. 2003a. Offsetting global $CO_2$ emissions by restoration of degraded soils and intensification of world agriculture and forestry. Land Degrad. Dev. 14:309–322.

Lal, R. 2003b. Soil erosion and the global carbon budget. Environ. Int. 29:437–450.

Lal, R., and J.M. Kimble. 1997. Conservation tillage for carbon sequestration. Nutr. Cycling Agroecosyst. 49:243–253.

Mataix-Solera, J., and S.H. Doerr. 2004. Hydrophobicity and aggregate stability in calcareous topsoils from fire-affected pine forests in southeastern Spain. Geoderma 118:77–88.

McLean, E.O. 1982. Soil pH and lime requirement. p. 199–224. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Mollitor, A.V., A.L. Leaf, and L.A. Morris. 1980. Forest soil variability on northern flood plains. Soil Sci. Soc. Am. J. 44:617–620.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon and organic matter. p. 539–580. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Neufeldt, H., D.V.S. Resck, and M.A. Ayarza. 2002. Texture and land-use effects on soil organic matter in Cerrado Oxisols, central Brazil. Geoderma 107:151–164.

Neupane, R.P., and G.B. Thapa. 2001. Impact of agroforestry intervention on soil fertility and farm income under the subsistence farming system of the Middle Hills, Nepal. Agric. Ecosyst. Environ. 84:157–167.

Olsen, S.R., and L.E. Sommer. 1982. Phosphorus. p. 403–430. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Pilbeam, C.J., B.P. Tripathi, D.P. Sherchan, P.J. Gregory, and J. Gaunt. 2000. Nitrogen balances for households in the mid-hills of Nepal. Agric. Ecosyst. Environ. 79:61–72.
Sahani, U., and N. Behera. 2001. Impact of deforestation on soil physicochemical characteristics, microbial biomass and microbial activity of tropical soil. Land Degrad. Dev. 12:93–105.
SAS Institute. 2004. SAS procedure guide. Release SAS 9.1.3 Service Pack 1. SAS Inst., Cary, NC.
Sherchan, D.P., R.M. Bajracharya, and K.R. Tiwari. 2003. Soil survey report of Pokhare Khola sub-watershed. Himalayan Degradation Project, Nepal.
Shrestha, B.M., B.K. Sitaula, B.R. Singh, and R.M. Bajracharya. 2004. Soil organic carbon stocks in soil aggregates under different land use systems in Nepal. Nutr. Cycling Agroecosyst. 70:201–213.
Shrestha, N.R., D. Conway, and K. Bhattarai. 1999. Population pressure and land resources in Nepal: A revisit, twenty years later. J. Dev. Areas 33:245–268.
Singh, B.R., and R. Lal. 2005. The potential of soil carbon sequestration through improved management practices in Norway. Environ. Dev. Sustainability 7:161–184.
Sitaula, B.K., R.M. Bajracharya, B.R. Singh, and B. Solberg. 2004. Factors affecting organic carbon dynamics in soils of Nepal/Himalayan region—A review and analysis. Nutr. Cycling Agroecosyst. 70:215–229.
Spaans, E.J.A., G.A.M. Baltissen, J. Bouma, R. Miedema, A.L.E. Lansu, D. Schoonderbeek, and W.G. Wielemaker. 1989. Changes in physical properties of young and old volcanic surface soils in Costa Rica after clearing of tropical rain forest. Hydrol. Processes 3:383–392.
Thapa, G.B., and G.S. Paudel. 2002. Farmland degradation in the mountains of Nepal: A study of watersheds 'with' and 'without' external intervention. Land Degrad. Dev. 13:479–493.
Thomas, G.W. 1982. Exchangeable cations. p. 159–165. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.
Tripathi, B.P., R. Gardner, K.J. Mawdesley, G.P. Acharya, and R.P. Sah. 1999. Soil erosion and fertility losses in the western hills of Nepal: An overview. Lumle Seminar Pap. 99/9. Lumle Agric. Res. Centre, Kaski, Nepal.
Trujilo, W., E. Amezquita, M.J. Fisher, and R. Lal. 1997. Soil organic carbon dynamics and land use in the Colombian Savannas: I. Aggregate size distribution. p. 267–280. *In* R. Lal et al. (ed.) Soil processes and the carbon cycle. CRC Press, Boca Raton, FL.
Vance, E.D. 2000. Agricultural site productivity: Principles derived from long-term experiments and their implications for intensively managed forests. For. Ecol. Manage. 138:369–396.
West, T.O., and G. Marland. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91:217–232.
Wolfgang, W., and K. Martin. 1997. Differences in concentration and fractions of aluminium and heavy metals between aggregate interior and exterior. Soil Sci. 162:323–332.
Yoder, R.E. 1936. A direct method of aggregate analysis and a study of the physical nature of erosion losses. J. Am. Soc. Agron. 28:337–351.
Youker, R.E., and J.L. McGuinness. 1956. A short method of obtaining mean weight diameter values of aggregate analyses of soils. Soil Sci. 83:291–294.
Young, A. 1988. Agroforestry for soil conservation. Sci. Pract. Agrofor. 4. CAB Int., Wallingford, UK.
Zinn, Y.L. 2005. Textural, mineralogical and structural controls on soil organic carbon retention in the Brazilian Cerrados. Ph.D. diss. (Diss. Abstr. 3197771.) Ohio State Univ., Columbus.
Zinn, Y.L., R. Lal, and D.V.S. Resck. 2005. Texture and organic carbon relations described by a profile pedotransfer function for Brazilian Cerrado soils. Geoderma 127:168–173.